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13.ABSTRACT *(Maximum 200 words)*

The grant was awarded for the purpose of purchasing a machine tool capable of performing microdrilling, micromilling, and electrical discharge machining (EDM) down to 25 micrometers in diameter. The primary scientific application of the fabriction capability was to enhance thermal performance at both the microscale and macroscale by machining microfeatures into thermal surfaces. This work is continuing and has achieved significant external funding. The Principle Investigator has expanded applications for micromilling and helped develop a process for the manufacture of micromilling tools down to 20 micrometers in diameter. This expanded application will be used to rapidly fabricate both molds and masks for the emerging field of micromanufacturing which is being conducted at the Institute for Micromanufacturing (IfM) at Louisiana Tech. Also during the proposal review process, the PI was able to demonstrate both the feasibility and application of microdrilling/micromilling/EDM with a temporary setup. The PI was able to secure an additional grant from the IfM to purchase a much more accurate and capable machine tool than that described in the original proposal. As a result of the capability demonstrated thus far with the temporary setup, researchers within the IfM have secured external grants from both the Army Research Office and the State of Louisiana to investigate microscale thermal enhancement.

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Micromilling, thermal enhancement

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Final Technical Report
AFOSR Grant F49620-93-1-0547
"Acquisition of Microdrilling/Micromilling/EDM Equipment"

Summary

The grant was awarded under the DOD-EPSCoR program for the purpose of purchasing a machine tool capable of performing microdrilling down to 25 micrometers in diameter, micromilling of features down to 25 micrometers in size, and fabricating features by electrical discharge machining (EDM) with electrodes down to 25 micrometers in diameter. The grant award was $111,000. The primary scientific application of the fabrication capability was to enhance thermal performance at both the microscale and macroscale by machining microfeatures into thermal surfaces. This work is continuing and has achieved significant external funding.

During the review period of the original proposal, the Principle Investigator began expanding the applications for micromilling and helped develop a process for the manufacture of micromilling tools down to 20 micrometers in diameter. This expanded application will be used to rapidly fabricate both molds and masks for the emerging field of micromanufacturing which is being conducted at the Institute for Micromanufacturing (IfM) at Louisiana Tech.

Also during the proposal review process, the PI was able to demonstrate both the feasibility and application of microdrilling/micromilling/EDM to the IfM. The PI was able to secure an additional grant of approximately $168,779 from the IfM to purchase a much more accurate and capable machine tool than that described in the original proposal. Because of the extended time required to specify, bid, and fabricate the new machine tool, delivery will not take place until early January 1995. In the interim, the PI has made significant demonstrations of the micromilling process on a temporary, manual machine which was purchased as an institutional match commitment on the original proposal. As a result of the capability demonstrated thus far with the temporary setup, researchers within the IfM have secured a total of $278,720 of external grants from both the Army Research Office and the State of Louisiana to investigate microscale thermal enhancement. Additional grants are pending.

1.a Scientific Objectives

The **primary objective** of the project was to develop a fabrication capability to support funded research in the areas wherein microscale surface features could be made to enhance the thermal performance of heat transfer surfaces. As a fluid flows over a surface with a different temperature, heat is transferred between the fluid and the surface. Because heat transfer requires a thermal gradient, and conduction and convection are dimensionally dependent, a thermal boundary layer ("thermal resistance") will result. Under normal circumstances, this boundary layer can become quite thick and provide a significant resistance to heat transfer, particularly in bulk laminar flow

conditions. If the boundary layer can be disturbed ("tripped up") by microscale features ("turbulators"), the result will be turbulence near the thermal surface and increased heat transfer. This concept is shown in **Figures 1 and 2**.

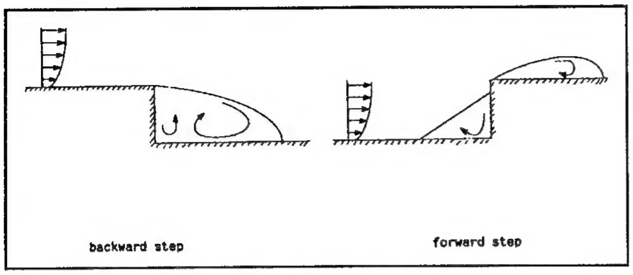

Figure 1 Typical fluid flow past a backward and forward facing step.

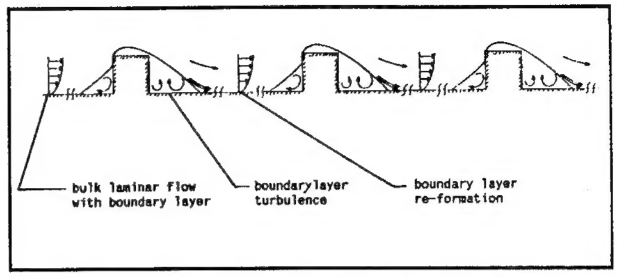

Figure 2 Typical geometry of repeated ribs

The **second objective** was to develop the micromilling process to a state where it could be used for other microscale fabrication processes. The microdrilling process is a mature area in conventional manufacturing and is widely used to fabricate such components as textile spinnerets. Electrical discharge machining (EDM) of holes down to 25 micrometers in diameter is also a mature process technology. The ability to EDM smaller diameter holes requires the special fabrication of small electrodes. Although this capability is available on the commercial market, it is being adapted within the IfM. A summary of the results of both objectives is presented in the next section.

1.b Project Status

To illustrate the concept of the **first objective**, and to develop base data on performance enhancement expectations, a study was conducted by Satish [1] wherein the process was modeled with the finite element method. The study investigated the influence of rectangular microturbulator length and spacing on heat transfer compared to a smooth surface for values of Reynold's number between 145 and 2000. The basic model is shown in **Figure 3**. All dimensions were normalized to the rib height "h" of 127 micrometers. The channel height was 3683 micrometers and the channel length was 3810 micrometers. The number, and consequently the distance between the ribs, was varied and the model repeated. The summary of the results is shown in **Figure 4**. It can be seen that at a Reynold's number of 2000, and 8 ribs with a spacing of 4h (508 micrometers) between ribs, the downstream heat transfer increased by over 30% than with a smooth-walled channel with the same dimensions. It may also be seen from **Figure 5** that with just two ribs with various spacing "d", the increase in heat transfer over a smooth-walled channel exceeds 40% in the downstream section of the channel for the higher Reynold's number.

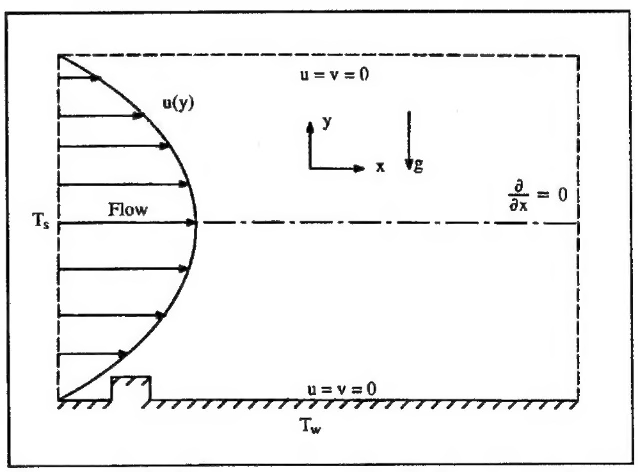

Figure 3 Model parameters for micro-turbulator

At present, this work is continuing by way of two external grants which have just begun. These grants are not under the direction of this investigator, however this investigator is serving as a senior consultant on both. These grants are more fully documented in section **1.d**.

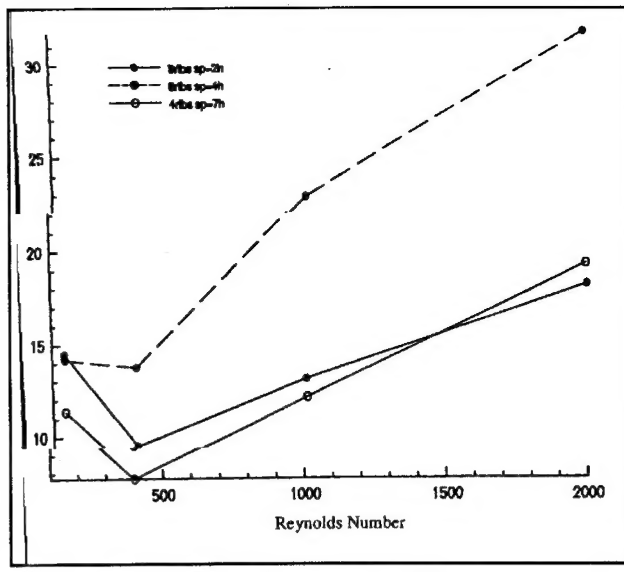

Figure 4 Heat transfer increase for two micro-turbulators spacings and Reynold's number

The status of the **second objective** is more fully developed. A temporary micromachining setup was purchased under the matching obligation of the grant. A National Jet, 7M manual microdrilling machine was purchased and modified to add computer control of the spindle feed and the workpiece feed. The 7M was also instrumented to measure the thrust force present in microdrilling holes in the 25 to 100 micrometer diameter range as a function of drill speed, drill feed, and drill peck depth. This data is currently being extrapolated to aid in the structural design of micromilling cutters. The wall surface roughness of the drilled holes was also measured under the various drilling conditions and documented as shown in section **1.d.**

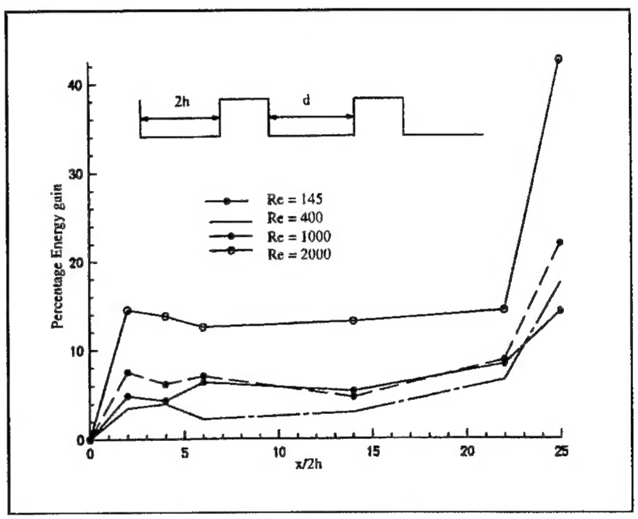

Figure 5 Heat transfer increase for two micro-turbulators with variable spacing

This work has led to the present status of the micromilling effort. Bear in mind, the results presented were performed on the temporary setup and not on the final machine purchased under this grant. A comparison between the two machines will be provided subsequently. The first generation micromilling cutter is shown in **Figure 6**. This is a 22 micrometer diameter four-fluted endmill cutter made with focused ion beam machining of a high speed steel blank. It is the smallest of its type in the world. This tool was used to machine features in copper, aluminum, and plastic with the 7M machine. Examples of the features produced are shown in **Figure 7**. This tool design was found to be impractical because of the fact that the workpiece material adhered to the surface and quickly "clogged" the cutting edges. This is shown in **Figure 8**. The next generation tool is shown in **Figure 9.** The large flats provide an area for material adhesion (which is a problem) but this does

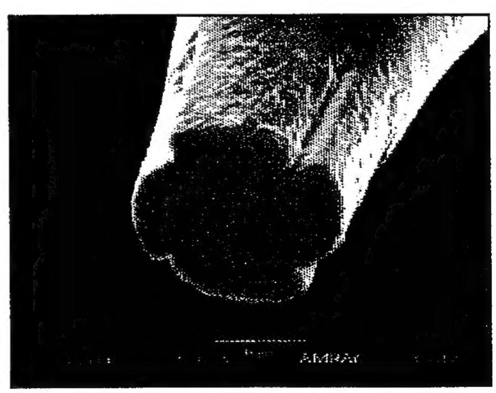

Figure 6 Four-fluted micro endmill made from high speed steel

not significantly hinder tool performance. Periodically, the tool must be cleaned in a chemical solvent to remove the buildup. Trenches in plastic, machined with this new tool, are shown in **Figure 10**. Work to extend this machining to aluminum and copper is currently underway and will be expanded when the newly purchased machine arrives in January 1995. All of this work will be eventually published.

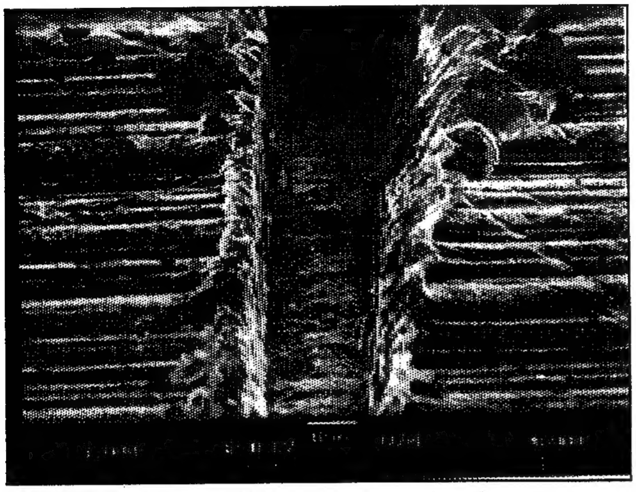

Figure 7 Micromilled trench in aluminum

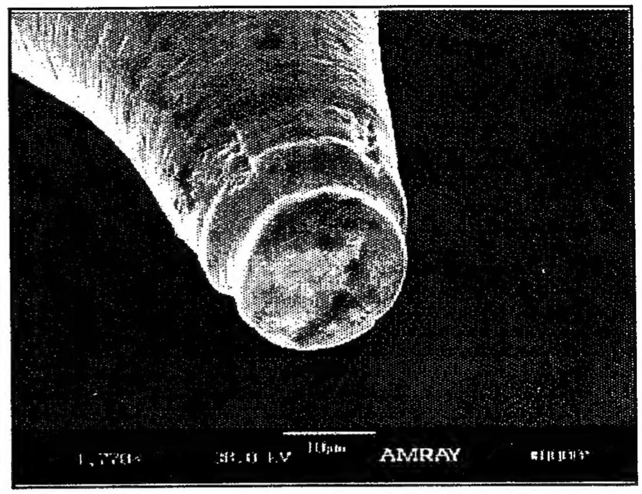

Figure 8 Adhesion of material to 4-fluted endmill

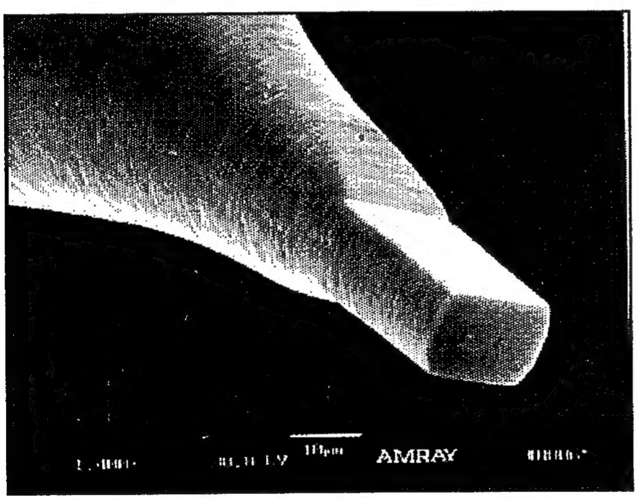

Figure 9 Two-fluted, spade-type endmill

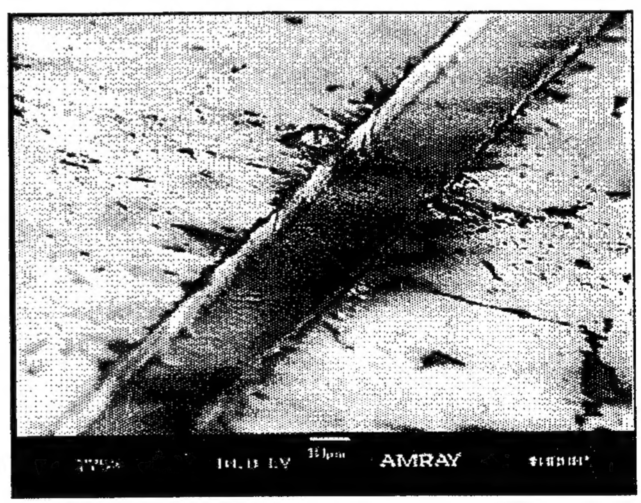

Figure 10 Micromilled trench in acrylic

Comparison of Machine Tools

	National Jet 7M	New Machine Tool
Work Travel	25mm, one axis only	150mm two axis
Spindle Travel	12mm	150mm
Work Accuracy	1 micrometer	1.25 nanometer
Spindle Accuracy	1 micrometer	1 micrometer
Spindle Speed	0 - 16,000 rpm	0 - 40,000 rpm
Min. Work Speed	35 μm/sec	0.12 um/sec or less
Capability	drill/mill	drill/mill/EDM/CMM/chem. mill

The current experimental setup is shown in **Figure 11** and the new machine tool purchased under this grant is shown in **Figure 12**.

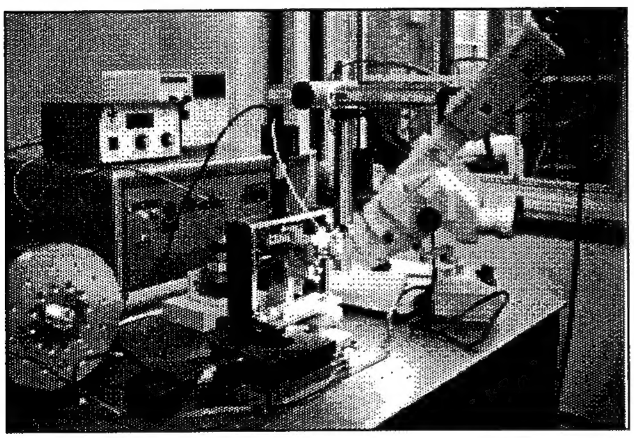

Figure 11 Current experimental setup for micromilling

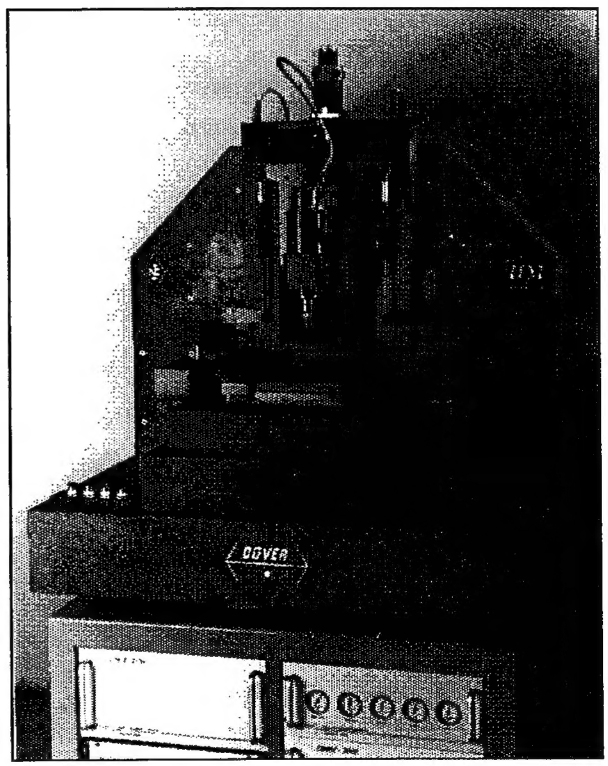

Figure 12 Equipment purchased from grant and matching funds (delivery January 1995)

1.c Publications

Because the grant was to purchase equipment, publications did not result from the grant action in and of itself. However, the research and process development which has resulted from the work leading up to the acceptance of the grant equipment is in draft form and continues. Current and planned publications include:

"Chapter 9.3.2 Precision Micromachining", (CR Friedrich and MJ Vasile), CRC Handbook of Industrial Engineering, currently in press.

"Focused Ion Beam Fabrication of Micromilling Tools", (MJ Vasile and CR Friedrich), planned submission to *Journal of Vacuum Science and Technology*, 1995.

"Micromilling Process Modeling and Application", (CR Friedrich, MJ Vasile, and R Nassar), planned submission to *ASME Journal of Engineering for Industry*, 1995.

"Micromilling Applied to Mold and Mask Fabrication in Micromanufacturing", (CR Friedrich), planned submission to *IEEE Journal of Microelectromechanical Systems,* 1995.

Other publications will surely result from the two grants which have been secured for the microscale thermal research using the purchased equipment. A list of those planned publications is not available at this time.

1.d Associated Personnel

The primary person on the grant was the PI. The National Jet Co. (LaVale, MD) is the prime contractor on the equipment and has had significant interaction with the PI. Dover Instruments, Inc. (Westboro, MA) is the subcontractor to National Jet and has also had significant interaction with the PI. There have been a number of degrees awarded, or about to be awarded, in the area of microdrilling and micromilling which relates to the grant activities or objectives.

1. **"Parametric Study of Heat Transfer Characteristics for Flow Over Surface Ribs"**, Vangipuram Satish, MS Thesis, Louisiana Tech University, May 1994.
2. **"Spatial Frequency Analysis of Microdrilled Holes in Aluminum"** Daniel Varghese, MS Thesis, Louisiana Tech University, August 1994.
3. **"Wall Surface Roughness of Microdrilled Holes in Aluminum"**, Yimin She, MS Thesis, Loisiana Tech University, November 1994.
4. **"Thermal Cool-Down Analysis of a Super Conducting System With Microgrooves"**, Mohammed Baig, MS Thesis, Louisiana Tech University, November 1994.
5. **"Thrust Force and Wall Roughness in Microdrilling Nickel"**, Chirayu Dave, MS Thesis (in manuscript), Louisiana Tech University, March 1995.
6. **"Thrust Force in Microspade Drilling of Aluminum"**, Ravi Muthu, MS Thesis (in manuscript), Louisiana Tech University, March 1995.
7. **"Optimal Design of Micromilling Cutters"**, Zhigang Qiu, MS Thesis (in manuscript), Louisiana Tech University, March 1995.
8. **"Precision Grinding of Microdrills and Micromilling Tool Blanks"**, Ramani Srinivasan (in manuscript), MS Thesis, Louisiana Tech University, March 1995.
9. **"The Micromilling Process for Trenches in PMMA and Aluminum"**, Bharath Kikkeri, MS Thesis (in progress), Louisiana Tech University, June 1995.
10. **"Adhesion of PMMA and Aluminum on High Speed Steel Micromilling Cutters"**, Thamyliniane Nagarajan, MS Thesis(in progress), Louisiana Tech University, June 1995.

Two external grants were obtained which address the enhancement of thermal surfaces with microscale features. The Principle Investigator in each case is Dr. Timothy Ameel, Assistant

Professor of Mechanical and Industrial Engineering at Louisiana Tech. Both grants will make use of the equipment purchased under AFOSR grant F49620-93-1-0547.

Title: Development of Phase Change Components for a Microclimate Control System
Source: ARMY Research Office
Period: 3 years
Amount: $213,720
Purpose: As the soldier of the next century may be required to perform in harsh environments, there is a growing need to provide a personal climate control system. Extremes of temperature, among other factors, seriously degrades the performance and perhaps survivability of the soldier. This project will investigate efficient techniques for providing both heating and cooling systems which are of low weight, low power consumption, and can be carried by the soldier as part of his/her equipment. The core of these systems is the ability to transfer heat to or from the body by means of enhances thermal exchange devices.

Title: Investigation of Microscale Phase Change Heat Transfer
Source: State of Louisiana LEQSF
Period: 2 years
Amount: $65,000
Purpose: Some processes are actually more efficient at the microscale than large scale. One such process is the transfer of thermal energy. This project will investigate various methods of transferring or extracting thermal energy from microscale thermal processes wherein a fluid undergoes a change of phase (such as water from liquid to steam). The ultimate goal of such a study is to develop new methods for heating and cooling buildings, or the recovery of industrial energy to reduce costs, pollution, and global warming.

1.e Interactions

i. Papers presented at meetings, conferences, seminars

"Complementary Micromachining Processes"(included microdrilling/ milling), Engineering Foundation Conference on Commercialization of MEMS, Banff, Alberta Canada, September 1994.
"Machining of PMMA in the Near-Cryogenic Region"(included micromilling applications), ASPE Annual Conference, Cincinnati, Ohio, October 1994.

ii. Consultative activities

None

1.f New inventions, specific applications.

As shown previously, the grant activities have resulted in the first and smallest micromilling cutters in the world. Although the process of fabricating micromechanical molds, masks, or structures may be patentable, there are no plans to pursue this at this time.

Certainly the specific applications are noteworthy. The reason that soft materials (copper, aluminum, and polymethyl methacrylate [PMMA]) are under investigation is two-fold. First, most electroformed microstructures are created in a PMMA mold as a result of x-ray lithography. The micromilling process will be able to **rapidly** create small numbers of molds for prototype development of micro systems. Secondly, masks used in x-ray lithography use gold as the x-ray absorber. *The micromilling process does not have the capability to directly compete with e-beam lithography processes for the production of x-ray masks.* However, the micromilling process can directly machine soft materials (such as gold) for the production of masks for prototyping microstructures with less precision and edge definition. Considering the fact that an x-ray mask costs $10,000 to $15,000 and may take 3 weeks or longer to have made at a commercial "mask house", the micromilling process may have widespread application in circumstances wherein a lower resolution mask is needed immediately and at much lower cost.

1.g Other statements

The purpose of the grant was to purchase a piece of equipment to expand research in the thermal enhancement area. This has been accomplished. External funding has been obtained which will use the equipment for that purpose. In addition, a new micromanufacturing process is being pioneered and will greatly expand when the equipment is made operational (January 1995). This process can be directly applied to fabrication of enhanced thermal devices. The grant **requested $111,000** from the AFOSR and was to be **matched with $16,000** from Louisiana Tech. **In reality, the match from Louisiana Tech exceeded $179,000 and has generated an additional $278,720 in research funding at Louisiana Tech.**